



# Numerical Investigation of Galactic Merger Utilizing High Performance Computing Architectures: Ancient Satellite Galaxy and Wandering Supermassive Black Hole

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過去の衛星銀河と銀河ハローを漂う超巨大ブラックホール)

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**Abstract**

Recent observations targeting on galactic halos have discovered many signatures of galactic mergers. Galactic merger is one of the key processes in the hierarchical structure formation scenario under the cold dark matter model. Galactic archaeological approaches based on comparison between observed data and theoretical models have contributed to unveil the formation and the evolution history of galaxies. Moreover, observations have revealed some correlations between the physical properties of galaxies and the mass of their central supermassive black holes (SMBHs). Coevolution of galaxies and SMBHs suggested by the observations is a hot research issue recently. State-of-the-art numerical simulation exploiting high performance computing architectures is a powerful and attractive tool to examine the current open-questions by comparing with the observations in detail. We have investigated the physical properties of an ancient satellite galaxy (Part I) and the current location of an expected SMBH wandering in the galactic halo (Part III) in terms of numerical galactic archaeology. Since a numerous parameter studies are necessary to complete these studies, we have developed a highly optimized  $N$ -body code efficiently works on a cluster equips many boards of graphics processing units (GPU) in Part II.

Photometric and spectroscopic surveys focused on the halo of the Andromeda galaxy (M31) have found many structures considered to be merger remnants such as the Andromeda giant stellar stream and stellar shells. To unveil a progenitor of the Andromeda giant stellar stream, we have investigated the interaction between an accreting satellite galaxy and M31 using an  $N$ -body simulation. A comprehensive parameter study with 247 models has been performed by varying the size and the mass distribution of the progenitor dwarf galaxy. We show that it is crucial the binding energy of the progenitor galaxy to reproduce the Andromeda giant stellar stream and the shell-like structures surrounding M31. As a result of simulations, the progenitor must satisfy a simple scaling relation among the core radius, the total mass and the tidal radius. Using this relation, we have successfully constrained the physical properties of the progenitors which have a mass ranging from  $5 \times 10^8 M_\odot$  to  $5 \times 10^9 M_\odot$  and a central surface density around  $10^3 M_\odot \text{pc}^{-2}$ . A detailed comparison between the result and the observed nearby galaxies indicates that the progenitor of the Andromeda giant stellar stream includes a dwarf elliptical galaxy, a dwarf irregular galaxy, and a small spiral galaxy.

We have developed a highly optimized code for collisionless  $N$ -body calculations based on direct summation. Our new optimization hides the latency to access the global memory, and the resulting CUDA

code has a peak performance of 1006.7 GFlop/s in single precision (assuming 26 floating-point operations per interaction) with a single NVIDIA Tesla M2090 board. Detailed performance analysis clarifies that the performance metrics of collisionless  $N$ -body simulations on GPU are only two quantities: first one is the number of running streaming multiprocessors and another is the clock cycle ratio of the latency to access the global memory and operations to calculate gravitational interaction. To improve the scalability of the OpenMP/MPI hybrid parallelized code, we have reduced the number of communications among multiple GPUs and have overlapped communications with computations to hide the communication time. The results of performance measurements show excellent scalability with superlinear scaling when the number of  $N$ -body particles per GPU is less than  $10^4$  and parallel efficiency approaching unity when the number of  $N$ -body particles per GPU is greater than  $10^4$ . The CUDA/OpenMP/MPI code has a peak performance of 255.5 TFlop/s when 256 NVIDIA Tesla M2090 boards are used, which is 75.0% of the theoretical peak performance.

In the hierarchical structure formation scenario, galaxies enlarge through multiple merging events with less massive galaxies. In addition, the Magorrian relation indicates that almost all galaxies host a central SMBH of mass  $10^{-3}$  of its spheroidal component. Consequently, SMBHs likely to wander in the halos of their host galaxies following a galaxy collision, although evidence of this activity is currently lacking. We have investigated a current plausible location of an SMBH wandering in the halo of M31. According to theoretical studies of  $N$ -body simulations, some of the many substructures in the M31 halo are remnants of a minor merger occurring about 1 Gyr ago. First, to evaluate the possible parameter space of the infalling orbit of the progenitor, we have performed numerous parameter studies using a GPU cluster, HA-PACS at University of Tsukuba. To reduce uncertainties in the predicted position of the expected SMBH, we then have calculated the time evolution of the SMBH in the progenitor dwarf galaxy from  $N$ -body simulations using the plausible parameter sets. The results show that the SMBH lies within the halo ( $\sim 20$ – $50$  kpc from the M31 center), closer to the Milky Way than the M31 disk. Furthermore, the predicted current positions of the SMBH are restricted to an observational field of  $0^\circ.6 \times 0^\circ.7$  in the northeast region of the M31 halo. We also discuss the origin of the infalling orbit of the satellite galaxy and its relationships with the recently discovered vast thin disk plane of satellite galaxies around M31.